Where are the Nearby Gas-Rich LSB Galaxies?

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ABSTRACT

The Fisher-Tully "10 Mpc Catalog of Late-Type Galaxies" (FT, 1981) is remarkably complete. Despite the considerable effort that has been spent searching for and cataloging low surface brightness (LSB) galaxies, almost no new HI-rich galaxies have been added to the volume to which the FT observations were both sensitive ($d < 10(M_{HI}/10^{8.2}M_{\odot})^{5/12}$ Mpc) and intended to be complete ($d < 10$ Mpc). It has not yet been demonstrated by the new surveys that HI-rich LSB galaxies are not properly represented in this catalog of nearby galaxies. Although new optical surveys are discovering heretofore uncatalogued galaxies at greater distances than the depth of the FT Catalog, they do not alter the completeness of the FT Catalog for HI-rich LSB objects. Thus, unless the galaxy population of the local volume is atypical, there is at present no evidence for a significant, new population of gas-rich galaxies that has escaped recognition until now.

Subject headings: galaxies: luminosity function, mass function

1. Introduction

It has long been suspected that there could be a population of galaxies with surface brightness so low that the galaxies low contrast against the dark sky would put them below the detection levels of optical surveys (Arp 1965, Disney 1976, Davies 1993). More recently, new survey material and computer-automated methods of analyzing survey plates have produced catalogs of galaxies specifically selected for low surface brightness (Binggeli et al 1985, Schombert et al 1992, Davies et al 1988, Impey et al 1996). Determination of the space density of these objects can be very difficult, since the optical brightness for the most extreme objects is so low that optical spectroscopy cannot provide redshifts.

Fortunately, the prototypical objects identified by several LSB surveys are rich in neutral gas, allowing redshifts to be measured in the 21 cm line (Longmore et al 1982, Bothun et al 1985a, Schombert et al 1992). The extreme of HI richness for LSB galaxies includes objects whose neutral hydrogen mass to optical luminosity ratio M_{HI}/L is well in excess of $1M_{\odot}/L_{\odot}$. At the

other extreme is a class of dwarf LSB identified in the Virgo and Fornax clusters, that remains undetected in the 21cm line to very sensitive limits ($\sim 2 \times 10^6 M_\odot$) (Bothun et al 1985b).

This paper addresses the completeness of our knowledge of the gas-rich segment of the nearby galaxy population. In particular, it asks the question whether recent surveys for LSB galaxies have added substantial numbers of a "new population" to older catalogs of optically selected galaxies. The base catalog is "The 10 Mpc Catalog of Nearby Galaxies" compiled by Fisher and Tully (1981; hereafter the FT Catalog). This catalog was designed to contain all late-type spiral galaxies and irregular galaxies with declination above $-33°$, Galactic latitude $|b_{II}| \geq 30°$ within $10h^{-1}$ Mpc of the Milky Way ($h = H_o/100$ km s^{-1}). The catalog was constructed from a complete inspection of the PSS using morphological classification to select galaxies expected to have redshifts less than 2000 km s^{-1}. The catalog was supplemented by including all galaxies except ellipticals from the UGC (Nilson 1973) with diameter $3'$ or greater and all late-type systems (Sd to Im) with diameter $> 2'$. In total, 1787 galaxies were observed in the 21cm line to a uniform flux density level, with detection reported for about 2/3 of the sample. The majority of the detections lie beyond 10 Mpc.

There are several newer catalogs of optically selected galaxies for which 21cm line detection has provided an efficient method for redshift determination. Here we choose to parameterize the population by HI mass, since the HI measurement provides both a distance indicator and a measure of each galaxy's detectability. The detectability function translates into a volume sensitivity that Briggs and Rao (1993) and Briggs (1997) have used to estimate the spatial density of gas-rich galaxies. Since members of the newer catalogs were observed at higher sensitivity than the FT observations (using the Arecibo Telescope, for example), examples of familiar nearby galaxies can be now detected at much larger distances, and thus they can be drawn from a larger volume, as will be shown to be the case for the new catalogs.

2. Analysis

The comparison of the new samples with the FT Catalog takes place in Figure 1, where each galaxy is registered as a point with its distance along the vertical axis and its measured HI mass along the horizontal. This type of plot enables a clear view of the detection limits for galaxies of different HI mass and indicates from which volumes the different samples are drawn.

The HI mass M_{HI} is a derived quantity that depends on each galaxy's distance; the effects of errors in distance and flux measurement on the location of the points are illustrated by the exaggerated error bars in the upper right panel. A distance error will move a point diagonally in these diagrams. Measurement errors for redshift are typically negligible once a galaxy is reliably detected, and it is peculiar velocity that dominates in displacing the galaxies along the diagonal error bar; since the displacement is very nearly parallel to the detection boundary, even very large uncertainties in distance fail to move galaxies across the the detection boundary. Flux errors cause horizontal displacements of typically less than 20 percent.

The FT Catalog, plotted in the upper left, has a clear detection HI limit that appears as a diagonal boundary between the area at the lower right, which is heavily populated, and the upper left, where only a few points spill over the boundary. A heavy line with slope $d_c \propto M_{HI}^{5/12}$ marks the expected form of the boundary, with the recognition that more massive galaxies (with larger HI mass) also rotate faster, spreading their signals into broader profiles of lower amplitude that are harder to detect. If all galaxies had the same velocity spread, d_c would be $\propto M_{HI}^{1/2}$. The effect of profile width, ΔV, on detectability was explored in greater detail by Briggs & Rao (1993) and is discussed only briefly here. The noise level, σ, in a spectrum that has been optimally smoothed to match the profile is $\sigma \propto 1/\sqrt{\Delta V}$. Since $M_{HI} = 2 \times 10^5 d_{Mpc}^2 \int S_{Jy} dV_{km/s} M_\odot$, the minimum detectable HI mass is $M_{HI} \propto 5\sigma\Delta V d^2 \propto d^2\sqrt{\Delta V}$, if the minimum detectable profile is modeled as a rectangle of height in flux density $\Delta S = 5\sigma$ and width ΔV. A sort of HI Tully-Fisher relation has $\Delta V \propto M_{HI}^{1/3} \sin i$ for galaxies with inclination i relative to the plane of the sky, leading to the result that $d_c \propto M_{HI}^{5/12} \sin^{-1/4} i$. In fact, enough information exists in the FT catalog to make a first order correction for inclination, which does indeed sharpen the detection boundary (Briggs & Rao 1993). On the other hand, since the inclination and size information is less well determined or not provided for all the samples and the $\sin^{-1/4} i$ factor is substantially different from unity for a only small fraction of a randomly oriented sample, we choose here to not take advantage of the information on inclination for the few catalogs in which it is given.

Other features in the distribution of FT points in Figure 1 are: (1) At the largest distances and largest masses, there is a fairly abrupt fall off in the density of points; this arises from the limited spectrometer bandwidth available at the time of the FT survey, which concentrated on the redshift range -400 to $+3000$ km s^{-1}, but the lack of coverage at higher redshift was not of concern since the sample was intended for completeness at $d < 10$ Mpc. (2) There is a concentration of points in a line at $\log 10.8$ Mpc $= 1.03$ due to the assumption that galaxies within $6°$ of the core of the Virgo cluster lie at this distance. (3) There are four points that lie on a horizontal line at 1 Mpc, due to assigning a distance of 1 Mpc to any galaxy with velocity less than 100 km s^{-1} (measured with respect to the centroid of the Local Group).

Distances and masses for the newer samples plotted in Figure 1 are computed in the same manner as those for the FT galaxies, assuming a Hubble Constant of 100 km s^{-1}Mpc^{-1}.

The detection boundary prevents the FT 10 Mpc catalog from attaining completeness to the full 10 Mpc depth for $M_{HI} < 10^{8.2} M_\odot$. However, the detection boundary is well defined and well understood, and the catalog can be tested for "completeness" within this boundary. Furthermore, the volume within which a given HI mass is detectable can be calculated, allowing the catalog to be used to estimate the space density of low M_{HI} objects that meet the late type morphological selection (Briggs 1997). The one-third of the FT sample that was undetected in the original catalog lies above the line by definition.

The detection boundary for the FT Catalog is replotted in the other panels of Figure 1 for comparison with the other samples. For most of the other samples, the high sensitivity of the

Arecibo Telescope detects galaxies far beyond the FT sensitivity boundary. On the other hand, the most striking result is that the new surveys add almost no galaxies to the volume of space where the FT Catalog was sensitive. Table 1 lists N_{CZ} and N_{SZ}, the numbers of new galaxies in each catalog falling in the FT Zone of Completeness (CZ) and the Zone of Sensitivity (SZ), respectively. The CZ and SZ are defined in Figure 1. (Note that the N_{CZ} galaxies in the CZ are a subset of those counted in N_{SZ}.) Since there is overlap between catalogs, construction of these counts requires exclusion of galaxies in the Schneider et al (1990) "Catalog of UGC Dwarfs and LSB Galaxies" that were already listed in the FT Catalog. Furthermore, there are galaxies in the Southern Extreme Late-Type Galaxies Catalog (Matthews & Gallagher 1996, Matthews et al 1995, Gallagher et al 1995) that fall at declinations or Galactic latitudes outside the region covered by the FT Catalog, and these are also excluded from the N_{CZ} and N_{SC} listed under Mathews et al in the table. The Schombert et al (1992) "Catalog of LSB Galaxies" adds no new members to the CZ and one to the SZ, while the automated selection of LSB objects in the catalog of Impey et al (1996) yields one detection in the CZ and one galaxy in the SZ at redshift less than 3000 km s^{-1}. In fact, the new surveys cover smaller solid angles Ω of sky than the FT Catalog, so that a weighting factor, Ω_{FT}/Ω, has been applied to the counts for the new catalogs (column (4) in the Table) for a fair comparison with the FT numbers. The very few new galaxies that are added to either the CZ or the SZ by any sample are located close to the detection boundary, as though they represent a simple incompleteness in the FT Catalog due to HI detection sensitivity.

The recent literature has other new catalogs of objects with a variety of selection criteria in addition to the catalogs plotted in Figure 1. For example, the six prototypes of the "dwarf spiral" class presented by Schombert et al (1995) lie at redshifts from 3200 to 6000 km s^{-1} – entirely outside the FT volume. The few dwarf galaxies from the sample compiled by Eder et al (1989, 1996) that fall within the SZ are previously cataloged objects with UGC numbers, and thus they also make no new addition to the inventory of nearby galaxies.

The few new galaxies added to the CZ (within $10h^{-1}$ Mpc) are low in HI mass, and thus they add only a few percent to the HI mass content of the nearby Universe. Estimates of average HI densities are listed in Table 1, resulting from summations over the members of each sample falling in the CZ or SZ:

$$\rho_{HI} = \sum \frac{M_{HI}}{V_m}$$

where $V_m = \Omega d_L^3/3$ for $d_L = d_c$ in the sensitivity bounded mass ranges and $d_L = 10$ Mpc or 30 Mpc in the large mass ranges of the CZ or SZ samples respectively. The density of $\sim 10^8 M_\odot$ is higher than most estimates (Fall & Pei 1989, Rao & Briggs 1993, Zwaan et al 1997) due to the bias caused by drawing the FT Catalog from the Local Supercluster (Felton 1977). It is clear from Table 1 that the new samples add a small number of galaxies and a tiny amount of HI mass to the volume where FT Catalog is sensitive.

3.   Discussion

If the recent surveys for low surface brightness galaxies were finding populations that are both (1) new and (2) cosmologically dominant repositories of matter, then the new detections should outnumber the old ones in any large volume. Instead, the new catalogs fill more distant shells in the d–M_{HI} space of Figure 1. Progressing from the FT diameter limit $\Theta_L \approx 2'$, through the $1'$ limit of the UGC to the $30''$ limit (at fainter isophotes) for Schombert et al (1992), Figure 1 shows that the catalog members lie at successively larger distance as the angular diameter limit is reduced. Within the Impey et al (1996) catalog ($\Theta_L \approx 30''$ for the bulk of the catalog), there is a gradient across the shell of HI detections, with the previously catalogued members of their sample falling at smaller distance and the new objects at larger distance. This behavior signifies that the new surveys are tending to select more distant examples of familiar types of galaxies, without adding to the density of galaxies or to the mass content of the Universe. The implication of Figure 1 is that the types of galaxies selected for their LSB properties by Schombert et al (1992) and by Impey et al (1996) must already be fairly represented by nearby, previously cataloged examples.

Why might there already be LSB galaxies in the historical catalogs? Much of the answer may be that the new catalogs look for LSB "disks" whose extrapolated central surface brightness lies below a set threshold and whose angular extent exceeds a set diameter limit. The extrapolation may lie beneath a luminous region at the center of the galaxy or patchy emission that is bright enough to attract the attention of the compilers of the earlier surveys. It may be the case that a fraction of the new LSB galaxies would be given other classifications if they were located close by. These kinds of nearby galaxies may have never been studied with large format detectors and observing techniques that would be sensitive to very extended LSB light without removing it during a "sky subtraction" step in the data reduction.

Is it possible that a gas-rich population of still lower optical surface brightness exists that could escape inclusion in these galaxy samples? Since the prototypical LSB galaxies that are most broadly represented in the new samples are rich in neutral gas (Schombert et al 1992), sky surveys in the 21cm line make effective tests of the existence of a gas-rich, extreme LSB population. A number of "blind surveys" in the 21cm line have produced HI-selected galaxy samples with significant numbers of members (Lo & Sargent 1979, Kerr & Henning 1987, Henning 1995, Weinberg et al 1991, Szomoru et al 1994, Sorar 1994, Spitzak 1996, Zwaan et al 1997, Schneider 1997). Subsequent optical follow up has found optical counterparts to more than 99 percent of the HI selected objects; the only exceptions appear at the very faint end of the mass distribution, where they make only small contributions to the integral mass density. The HI selected objects are apparently drawn from the same population of extragalactic system that is already cataloged by optical selection. Reported "intergalactic HI clouds" have so far been subsequently associated with visible galaxies, either as tidal remnants (e.g. Chengalur et al 1995) or as a bound ring (Schneider 1989).

4. Conclusion

There is no evidence so far that new catalogs of LSB galaxies are identifying a new population. Clearly, traditional catalogs such as the UGC, CGCG (Zwicky et al 1961), etc have completeness limits, and new surveys that are sensitive to lower surface brightness or accept galaxies of smaller angular diameters will always add distant galaxies that have not already been catalogued. Indeed, the new catalogs appear to be adding detections in successively more distant shells in the d vs. M_{HI} diagram. The new surveys are showing that the catalog of Fisher and Tully (1981) is remarkably complete for the nearby volume, and the implication is that it must already contain a balanced representation of gas-rich LSB galaxies.

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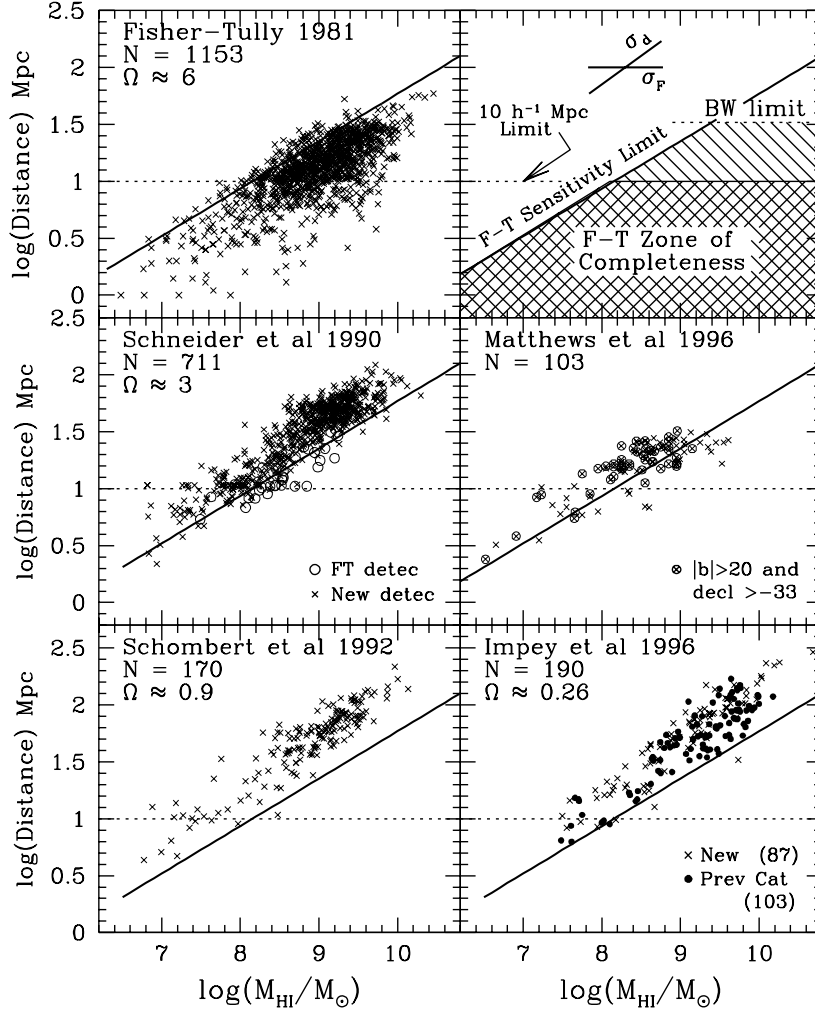

Fig. 1.— Depths of the HI-rich galaxy samples. For five galaxy samples, the galaxies detected in HI are plotted at their measured distance as a function of their HI mass. An estimate for the HI detection limit for the Fisher-Tully (1981) sample $d_c \propto M_{HI}^{5/12}$ is drawn as a heavy solid line in all six panels. A horizontal dotted line in each panel indicates 10 Mpc ($H_o = 100$ km s^{-1} Mpc^{-1}). The number of galaxies detected, N, and the survey solid angle, Ω, for each catalog are indicated. A subset of the Schneider et al catalog was already detected by FT, and these are indicated by open circles. Points representing galaxies in the Matthews-Gallagher samples falling at $|b| > 20°$ and declination $> -33°$ are enclosed in circles. A total of 103 of the 190 galaxies detected in HI in the Impey et al (1996) survey had been previously catalogued. The *top right panel* shows a crosshatched region where the FT Catalog is nominally complete (the Completeness Zone, CZ); the FT Sensitivity Zone (SZ) is shaded and consists of the entire region below the F-T sensitivity limit (including the CZ) and within the $d < 30h^{-1}$Mpc bandwidth (BW) limited depth of the FT survey. The effects of a factor of 3 error in measuring flux and a factor of $\sqrt{3}$ in determining the distance are indicated.

Table 1. Detections in the F-T Zones of Completeness and Sensitivity

Catalog	Ω_s Sterad	N_{CZ}	N_{SZ}	$\frac{\Omega_{FT}}{\Omega_s}N_{CZ}$	$\rho_{HI}[CZ]$ $M_\odot Mpc^{-3}$	$\rho_{HI}[SZ]$ $M_\odot Mpc^{-3}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Fisher-Tully 1981	~6	315	1017	315	10.8×10^7	5.8×10^7
Schneider et al 1990	~3	12	28	24	2.4×10^6	2.7×10^6
Schombert et al 1992	~0.9	0	1	0	0	3.8×10^5
Matthews et al 1996	<1	1	8	>6	$>5\times10^5$	$>2.1\times10^6$
Impey et al 1996	0.26	1	2	23	1.7×10^6	4.0×10^6

Note. — Columns: (1) catalog by authors, (2) survey solid angle (steradians), (3) N_{CZ}, number of new galaxies within FT zone of completeness, (4) N_{SZ}, number of new galaxies within FT zone of sensitivity, (5) N_{CZ} from column 2, scaled to the solid angle, Ω_{FT}, of the FT Catalog, (6) average HI mass density within the FT zone of completeness ($d < 10h^{-1}$ Mpc) contributed by each survey, (7) average HI mass density within the FT zone of sensitivity from each survey.